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CONNECTOR DESIGN TECHNIQUES TO AVOID RFI.(U)

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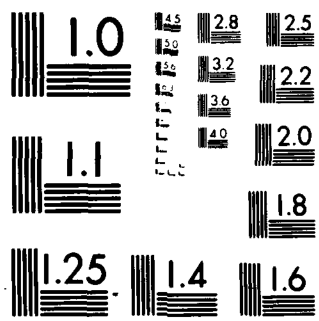

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CONNECTOR DESIGN TECHNIQUES TO AVOID RFI*

(10) Charles E. Young
Satellite Communications Branch
Communications Sciences Division

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BACKGROUND

An ~~earlier~~ paper[1], presented at the Ninth Annual Connector Symposium, gave detailed experimental evidence of the serious RFI levels produced by commonly available RF connectors which use ferromagnetic materials (iron, nickel, cobalt or their alloys) for electrical conductors. For example, the body structure of a wide variety of precision made coaxial connectors and adapters are currently manufactured only from stainless steel, type 303, a ferromagnetic alloy. To cut cost and provide a corrosion resistant finish, nickel plating, another ferromagnetic material, has been almost exclusively substituted for silver or gold, previously employed to plate brass stock connectors. That such materials could be considered for electrical conductor service is difficult to understand because of the known nonlinear effects of even minute quantities of ferromagnetic contaminants in RF systems.† Use of ferromagnetic materials, however, has become so widespread that silver or gold plated brass (nonferromagnetic) devices, which had been standard for many years, are no longer readily available as "off-the-shelf" items but must be specially ordered in quantities (500 or more) to obtain reasonable production cost.

As shown in reference (1), connectors fabricated from ferromagnetic materials typically produce IMG power levels 3 to 5 orders (1000 to 100,00 times) higher (worse) than without. Obviously such interference levels cannot be tolerated in todays highly sensitive communication systems. The ferromagnetic connector RFI problem came to light in 1975 during the Naval Research Laboratory's investigation of passive component nonlinearity and means for its reduction required by the Fleet Satellite Communications (FLTSATCOM) system, then under development.

To alert the communications community of the ferromagnetic connector nonlinearity problem, reference (2) was issued September 16, 1975 in advance of formal reporting and published under the government-Industry Data Exchange Program (GIDEP) as Alert No. Y1-A75-01, October 6, 1975. The experimental findngs of ferromagnetic connector nonlinearity are substantiated through theoretical analysis.[3] A literature search‡ and discussion with others in the communications field also confirms the NRL findings.

Although the ferromagnetic connector nonlinearity problem has been reported and widely discussed during the past 3 years, very little action has been taken to correct the problem. Many companies are continuing business as usual with a "take it" or leave it" attitude. It has been suggested that

*Presented at the Eleventh Annual Connector Symposium, Cherry Hill, N.J., 25-26 Oct 1978.
†The references listed at the end of this chapter are only a small sampling of the available literature.
‡The ferromagnetic nonlinearity problem has been recognized, almost from the beginning of electrical communications. The history of resistance anisotropy in ferromagnetic metals goes back to 1857 (W. Thomson) and that of the anomalous Hall effect to 1893 (A. Kundt). See references (4), (5), (6), (7), (8), and (9) for further details.

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only the Navy is having a problem but this is not true. Cost reduction and corrosion resistance, if not accompanied with full operational capability, is not justification for deviating from sound metallurgical and mechanical design practices which have been established through basic research and development over many years.

This chapter was orginally intended to identify coaxial connector problems found in the NRL study other than the ferromagnetic nonlinearity reported.[1] However, because of the seriousness of the ferromagnetic problem, a further discussion of connector nonlinearity, as related to the basic concept of "skin depth" conductor current flow at RF (indicated but not developed in the earlier paper) will be presented. Both ferromagnetic and contact nonlinarity, the two major sources of RFI by connector hardware, will be discussed.

BASIC SYSTEM REQUIREMENTS

The need for extremely linear passive components, including RF connector hardware, is evident by considering antenna, receiver, and transmitter requirements in a typical communication center where simultaneous reception and transmissions are involved.

Antenna System Configurations

Figure 1 illustrates schematically the two basic systems employed in radio communication centers: (a) the single antenna diplexed receive/transmit system and (b) the use of separate antennas for reception and transmission. In terms of system size, weight, and cost, the single antenna diplexed (combined) receive/transmit system is of course preferred, as it avoids the need for two or more antenna structures and signal feeds for the required receivers and transmitters. However, the problem of self interference is potentially worse. Electrical nonlinearities within the multicoupler-diplexer filters or connecting RF hardware to and including the antenna stuctures will convert a fraction of the multiple signal transmit power into IMG product signals. The IMG signals that fall within the receive frequency bands and are not well below receiver thermal noise (amplitude) will interfere and degrade weak signal reception.

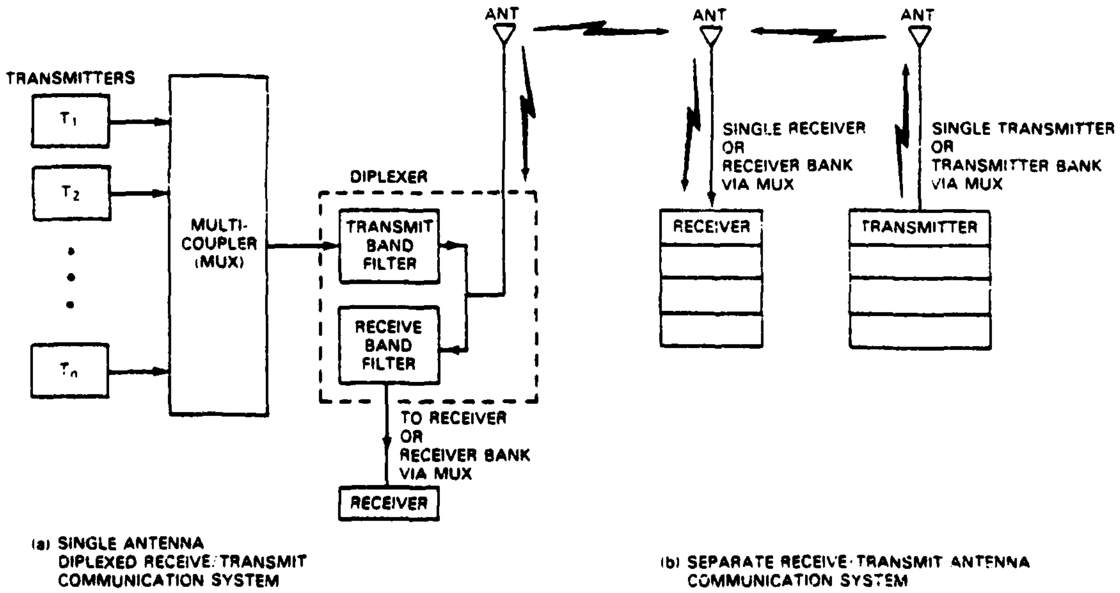


Fig. 1 — Radio communication center receiving/transmitting system arrangements

To avoid conducted RFI, as in the diplexed system, an attractive alternative (at sufficiently high frequencies) is the use of separate receive and transmit antennas spaced as far apart as is practicable. Free space attenuation between isotropic (nondirectional) antennas is:

$$\frac{P_r}{P_t} = \frac{\lambda^2}{(4\pi D)^2} \tag{1}$$

where

P_r = received power in watts

P_t = transmitter power in watts

λ = signal wavelength in meters or feet

D = separation in same units as λ

The attenuation, α, in decibels (dB) is:

$$\alpha = 10 \log \frac{P_r}{P_t} = 10 \log [\lambda^2/(4\pi D)^2] \tag{2}$$

At D = λ, the free space attenuation is 22 dB. For twice the separation, D = 2λ, attenuation is increased 6 dB, giving an isolation of 28 dB. An additional 6 dB is obtained for each doubling of the separation, as shown in Table 1.

Table 1 — Attenuation between Isotropic Antennas

Separation (ft)	λ	2λ	4λ	8λ	16λ	32λ
Attenuation (dB)	22	28	34	40	46	52

In practice, antennas are directional (not isotropic) and the isolation is increased by the directivity obtained with each antenna. At UHF, isolation between receive and transmit antennas can be in the order of 50 dB (as obtained on FLTSAT). This value of isolation not only reduces the transmit antenna IMG signal coupling to the receive antenna, but also reduces fundamental transmit signal levels impinging on the receive antenna, thereby minimizing nonlinear responses in the receive antenna system. Unfortunately, at HF it is difficult, if not impossible to obtain this order of isolation because of the longer wave length, λ, and reduced antenna directivity.

Receiver Sensitivity (Noise) Threshold-IMG Requirements

State of the art receiving systems can readily provide noise figures (NF)* in the order of 4 dB or less. To avoid sensitivity degradation, IMG products which fall in the receive frequency band must be less than receiver thermal noise by approximately 20 dB. Table II indicates the parameters used to to determine the maximum permissible IMG level in a 100 Hertz (Hz) signal bandwidth and the equivalent power in decibels relative to 1 milliwatt (dBm). The above receiver noise threshold-to-IMG margin of 20 dB represents a sensitivity degradation of only 0.04 dB and is imposed upon spacecraft and other critical system designs, not only to insure negligible RFI but to also provide some margin for system degradation with time and under environmental extremes. An IMG level equal to receiver thermal noise (−150 dBm for the 4 dB NF receiver) represents a 3 dB degradation in threshold sensitivity, the maximum acceptable RFI limit for most communication systems. Even this degree of performance is not attainable with ferromagnetic RF connector hardware, as shown.

$^*\mathrm{NF} = 10 \log \left[1 + \frac{\text{Rec. Noise Temp}}{290°\,\mathrm{K}}\right]$

Transmitter Requirements

Transmit signal levels vary but for discussion purposes may be assumed to be in the order of 100 watts, equal to +50 dBm. A receiver RFI limit of −170 dBm, or less, as indicated in Table II requires that transmit IMG products falling in the receive frequency band be at least 220 dB below +50 dBm, the desired transmit signal levels. With closely spaced receive and transmit frequency bands, less than 8 percent of band centers in the FLTSAT system, sufficient IMG attenuation has only been achieved with separate antennas and very linear RF hardware. The 3rd order IMG level of a diplexed system, carefully built to test RF connector hardware and described in reference (1), measured somewhat less than −140 dBm with +50 dBm total power from the diplexer output (antenna) port. This represents a diplexed system residual IM conversion of −190 dB or about 30 dB worse than desired.

Table II — Receiver Sensitivity/IMG Threshold

Parameter	Numerical Value	Equivalent
Boltzmann's Constant, k	1.38×10^{-23} Joule/ Kelvin	−198.6 dBm/Hz K
Ant. Noise Temp (~19°C)	290 K	
Rec. Noise Temp	440 K	
System Noise Temp	730 K	+28.6 dB K
Bandwidth	100 Hz	+20.0 dB
Rec. Noise Threshold	10^{-18} watts	−150.0 dBm
Margin (rec. Thresh/IMG)	100/1	−20.0 dB
Max IMG RFI level	10^{-20} watts	−170.0 dBm

Since IMG products appear to drop about 10 dB per order, a diplexed system becomes a viable technique, if a sufficiently wide unused band of frequencies (guardband) is allowed between the receive and transmit frequency bands to reject the 7th and lower order products. However, it should be noted that IMG products, or harmonics radiated by any system, whether diplexed or not, may fall into receive frequency bands of other nearby systems and there cause RFI and/or sensitivity degradation. Elimination of nonlinear passive components is therefore still required.

CONNECTOR IMG DATA

To again show the excessive RFI produced by commonly used ferromagnetic connectors relative to that permitted in the communication systems just described, characteristic connector IMG data will be presented. The NRL test set and extensive connector IMG data were described in detail in reference (1).

Ferromagnetic IMG as a Function of Product Order

Third order IMG, being the lowest order and largest interference which can occur in the receive frequency band of a multiplex system (with guardband width less than the transmit frequency band, as in FLTSAT) usually determines the degradation of threshold sensitivity. The extremely high level of 3rd order IMG by ferromagnetic connectors, however, implies the presence also of potentially degrading higher order IMG products. These characteristics were investigated, using connector samples V, A and U from the earlier study as the device under test (DUT) shown in Figure 2. To identify each connector/adapter of the large number tested, letters were assigned followed by a parenthesized indicator of each device. Sample "V" was a standard UG-30C/U kovar hermetic seal (HS) RF coaxial adapter. Sample "A" was a precision "N" double jack (female) adapter which uses a stainless steel body for the coaxial outer conductor. Sample "U" was a standard UG-29 nickel plated (NP) adapter.

Sample V was one of the ten UG-30C/U kovar hermetic seal coaxial adapters, originally tested. This commonly employed device is extremely nonlinear because the center conductor through the glass

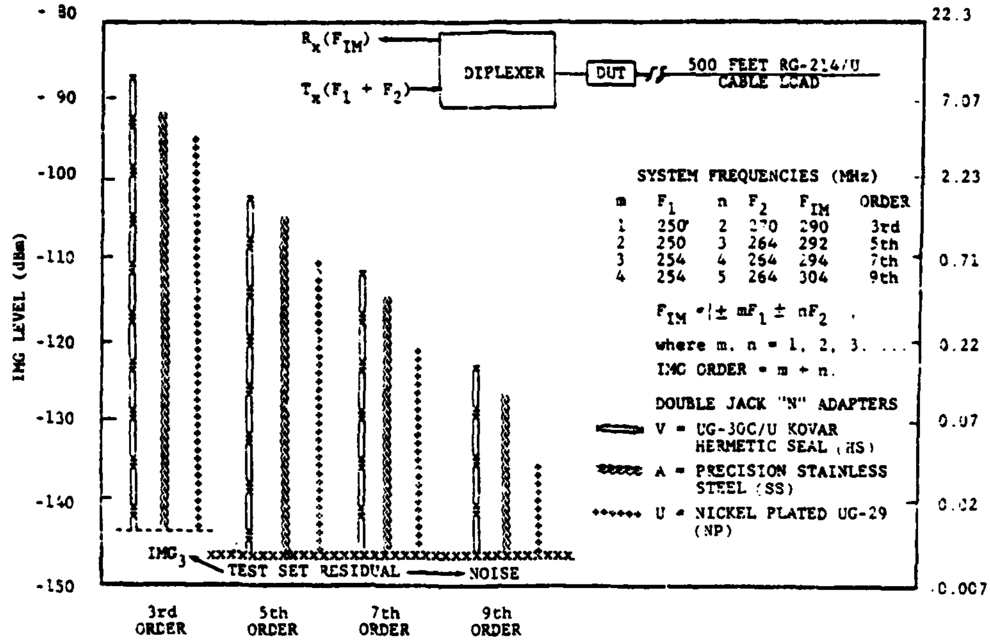


Fig. 2 — Ferromagnetic connector/adapter IMG as a function of product order

seal and the metallic rim around the glass seal is made of kovar or similar ferromagnetic material. Kovar contains 99.7% ferromagnetic materials (iron, nickel and cobalt) and is generally the most nonlinear of devices tested. Note its very large IMG level for all orders of nonlinearity shown in Figure 2.

For many years kovar was the primary material employed for hermetic seals of reported RFI problems, documented as early as 1966[11]. Fortunately, a new non-ferromagnetic hermetic seal has been announced recently. The Space and Communication Group at the Hughes AirCraft Company, Los Angeles California, have reported the successful development of a non-ferromagnetic hermetic seal because of ferromagnetic IMG RFI problems encountered in their MARISAT and related communication systems. The new seal is reported to have high RF power capability, no IMG problems and to withstand repeated thermal shocks from liquid nitrogen to boiling water with no detectable leakage. The radio communications community is in urgent need of such a device.

From Figure 2, it is evident that IMG from the stainless steel connector is only slightly less than that from the kovar device and that the nickel plated device is almost as nonlinear. The drop of about 10 dB for each progressively higher order of IMG is typical of known nonlinear devices. More importantly, the higher orders of IMG from all three ferromagnetic connectors far exceeded the 3rd order IMG residual of the diplexed test set (∼−144 dBm) and of course the test set noise threshold of ∼−147 dBm. (Note that 5th and higher order IMG from the test set alone was below noise threshold and therefore not detected.) Actually 11th order IMG from the nickel plated device, 13th from the stainless steel and 15th from kovar measured above the test set noise threshold.

Nonferromagnetic Connector IMG Comparison

Standard silver plated (non-ferromagnetic) UG-29 adapters, when operated as the DUT typically did not change the test set 3rd order IMG residual (∼−144 dBm), an indication that connector 3rd order IMG was below the test set residual by at least 10 dB*, or ∼−154 dBm. Higher orders of IMG

*Assuming simple power addition, a test set plus DUT IMG level 0.5 dB greater than that of the test set alone indicates that DUT IMG (alone) is theoretically 9.6 dB below the test set and hence that much more linear.

with nonferromagnetic connectors were also below the test set detection noise threshold, as might be expected. Except for obviously defective adapters, even a random selection of silver plated non-ferromagnetic devices usually gave IMG levels (DUT + test set) no more than 3 dB above that of the test set alone, indicating a maximum DUT IMG = test set IMG, or ~−144 dBm. The vastly superior performance of the non-ferromagnetic connectors is not indicated in Figure 2, but was illustrated in numerous data comparisons in reference (1). The necessity to exclude ferromagnetic materials as electrical conductors in RF connector hardware is clear.

IMG MECHANISMS

Like thermal noise, nonlinearities are present to some degree in all elecrical networks. Many IMG mechanisms have been postulated[12,13,14,3] but the two major sources of nonlinearity encountered in RF connector hardware are:

(1) Imperfect metal-to-metal electrical contacts, and

(2) Use of ferromagnetic materials for electrical conductors.

The problem of imperfect contacts is widely recognized, but nonlinearity due to ferromagnetic conductors is less well known. The nonlinearity of ferromagnetic conductors is related to the change in permeability experienced with current flow as described next.

Skin Depth*

It is well known that alternating current is not uniformly distributed over the cross section of a homogenous conductor (as with direct current) but is displaced more and more to the conductor surface as the frequency is increased. For very high frequencies, practically the entire current is concentrated in a very thin layer at the surface called the "skin depth", of the conductor. The skin depth, δ, at which the current density drops to $1/e$(~37%) of its value at the conductor surface is given by

$$\delta = (\pi f \sigma \mu)^{-\frac{1}{2}} \tag{3}$$

where f is the frequency of operation, and σ and μ are the conductivity and permeability, respectively, of a given conductor. If the conductor is a nonferrous metal, such as silver, a linear relationship exists between the resulting magnetic flux, B, and the magnetic field intensity, H, with current flow; i.e., $B = \mu H$ where μ is a constant, very close to that of free space, $\mu_0 = 4\pi \times 10^{-7}$ henrys per meter (h/m). For this linear relationship, δ can be analytically determined. Silver, for example, which has the largest conductivity, $\sigma = 6.15(10^7)$ mhos/m, (least resistivity, $\rho = \frac{1}{\sigma}$, or loss of any metal at normal temperatures) has a skin depth of $\sim 2 \times 10^{-6}$ meters (m) at 1 GHz, (10^9 Hz). The minimum silver plating, in accordance with Federal Specification QQ-S-365a for nonferrous base metal conductors is 0.0005 inch ($\sim 12.7 \times 10^{-6}$ m) which provides >6 skin depths at 1 GHz, and thus conducts more than 99.8% of the total current.

On the other hand, if the current carrying conductor is a ferromagnetic material, μ is not constant but varies with H in a very nonlinear manner. B depends not only on H but also on previous values of H, the well known hysteresis effect. The skin depth equation is therefore nonlinear with "memory" and cannot be solved analytically. Of greater concern, however, is the variation of skin depth caused by permeability change; which is equivalent to a nonlinear circuit impedance change—being a function of instantaneous current amplitude. This effect is evident in the following numerical approximations of skin depth for nickel plating, based in part upon data from reference (9). The hysteresis loop

*An excellent analytical development of skin effect, as well as an interesting historical sketch of its discovery, starting with Maxwell in 1873, is given in reference 15.

(memory) of nickel at room temperature is shown in Figure 3, and the nonlinear change in relative permeability, μ_r, as a function of field strength, H, is shown in Figure 4. These parameters are comparable for other ferromagnetic materials and may therefore be used as a model.

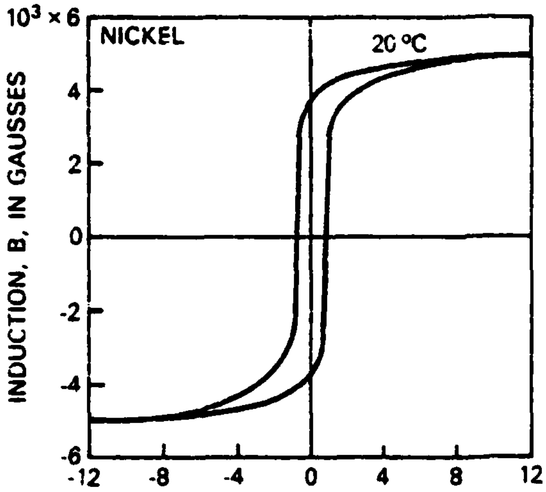
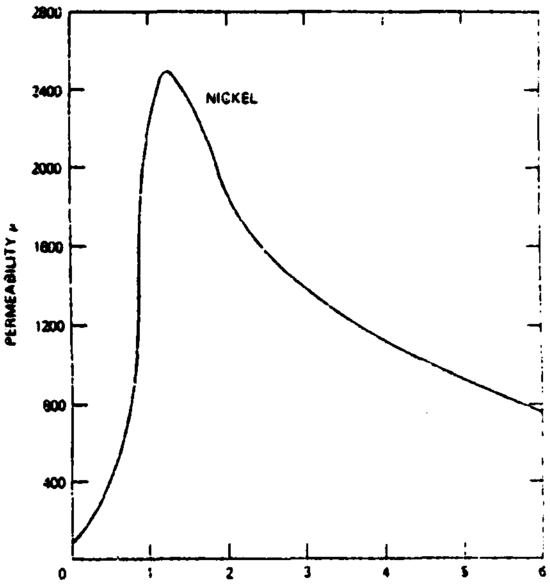


Fig. 3 — Ferromagnetic hysteresis nonlinearily



FIELD STRENGTH H (OERSTEDS) ∝ I (CURRENT)

Fig. 4 — Ferromagnetic permeability nonlinearity

If one first assumes an extremely small signal current amplitude, the initial permeability of nickel, $\mu_i = 4\pi \times 10^{-5}$ h/m, may be used. The conductivity of nickel, σ_{Ni} is $\sim 1.3 \times 10^7$ mhos/m. These values result in an initial skin depth, δ_i of $\sim 4.4 \times 10^{-7}$m at 1 GHz., a value approximately 1/5 of that for silver. Since the thickness of nickel plating on connectors typically measures 10^{-5}m (> 20 skin depths) or more, the entire current is carried by the nickel plated surface. Besides the nonlinearity problem, a minute skin depth intensifies the effects of surface imperfections such as scratches, holes, oxide contaminants, etc. creating anomalous skin current paths and erratic metal-to-metal contact junctions.

As signal current increases, the permeability of nickel increases, reaching μ_{max}, 10 to 100 times μ_i. This further decreases skin depth by a factor of 3 to 10 times. Beyond some critical current, however, permeability decreases, finally reaching saturation, $\mu_{sat} = 4\pi \times 10^{-7}$ h/m (free space); resulting in a maximum skin depth for nickel of approximately twice that for silver, because of the poorer conductivity of nickel. Thus, a very large nonlinear change in skin depth, by at least an order of magnitude, can be visualized as a function of current flow. The additional nonlinear effects due to hysteresis are not possible to evaluate numerically.

There are undesired effects other than the nonlinear permeability change which disqualify ferromagnetic materials for use as electronic connectors. Besides the low conductivity, an effect exhibited by ferromagnetic metals is the anisotropy of electrical conductivity; different values for different current and/or field directions. Also, magnetoresistivity, the change in resistance associated with a change in magnetization, weakly found in all metals, is orders higher in ferromagnetic materials. Magnetostriction, the change in physical dimensions of a ferromagnetic material in a magnetic field is another undesired effect for an electrical connector. See the listed references for further information.

As noted earlier, non-ferromagnetic metals exhibit constant permeabilities, which differ only minutely from that of free space; being either paramagnetic (slightly larger than μ_0) or diamagnetic (slight less than μ_0). Skin depth is predictable and independent of current magnitude except for an extremely small thermal modulation (discussed in Chapter V and in reference 13, for example). Figure 5 is a chart giving skin depth, δ, in parts of an inch for various metals over a wide range of frequencies (10 Hz to 1 MHz using the top and right hand scales, and 100 kHz to 10 GHz, using the bottom and left hand scales). The non-ferromagnetic metals, solid lines, exhibit increasing skin depths, as conductivity decreases, relative to that of silver. The ferromagnetic elements, nickel, Ni, and iron, Fe, shown dashed, indicate even less skin depth based upon their initial permeabilities, μ_i, as plotted. Recall, however, that ferromagnetic metal skin depth is dependent upon instantaneous current magnitude and is therefore modulated below and above these values with alternating current flow. For example, nickel, at sufficiently high current (permeability saturation, μ_{sat}) should approach the skin depth of brass because of their comparable conductivities.

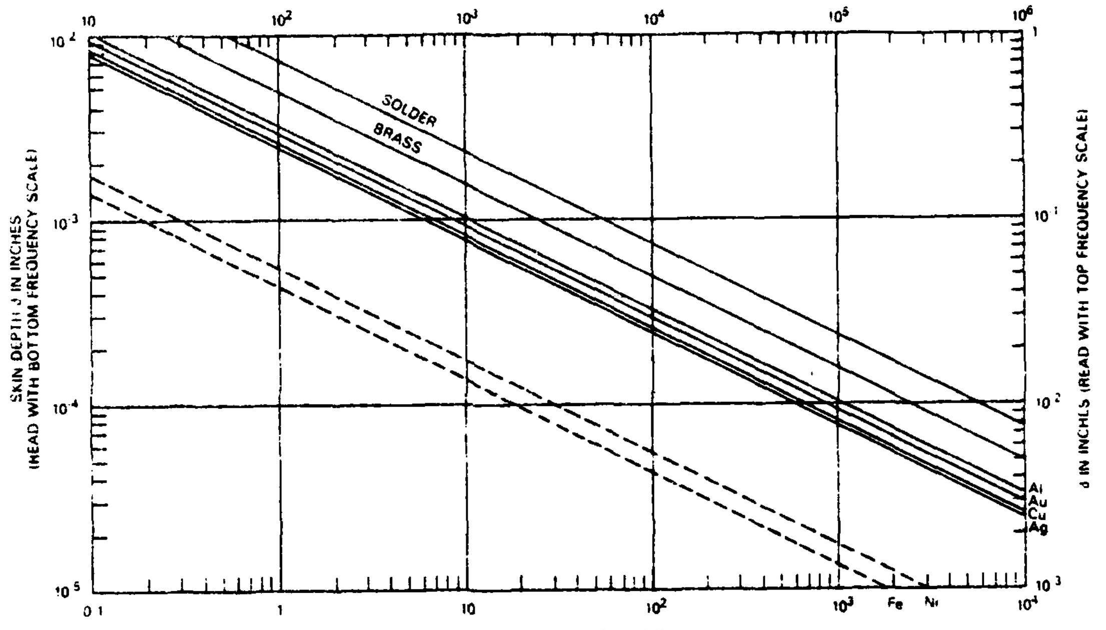


Fig. 5 — Conductor skin depth as a function operating frequency

The most important consequence of conductor skin depth is the greatly increased impedance (power loss) with alternating current (ac) flow, as compared to that with direct current (dc) flow. This effect is shown in Figure 6 for the same metals and frequency range presented in Figure 5. The surface resistivity, R_s,* defined as the resistance in ohms of a surface of equal length and width, becomes

$$R_s = \frac{\rho}{\delta} = (\pi f \mu \rho)^{\frac{1}{2}}. \tag{4}$$

Note, the superiority of silver (Ag) relative to all other metals as well as the maximum resistive (power) loss shown for the ferromagnetic metals, Ni and Fe.

Contact Imperfections

An illustration of a perfect contact between the end surfaces of a cylinder and a flattened sphere is shown in Figure 7. The shaded area represents the effective ac conductor surface while the total cross section represents the far greater dc conductor contact area. This drawing points up the fallacy of rating a coaxial connector in terms of some minimum dc resistance, as done by connector manufacturers. A much more meaningful measurement would be the RF resistance, at say, the upper frequency limit of the device.

*Schelkunoff, reference 16, p 550, defines R_s as the intrinsic resistance of the material.

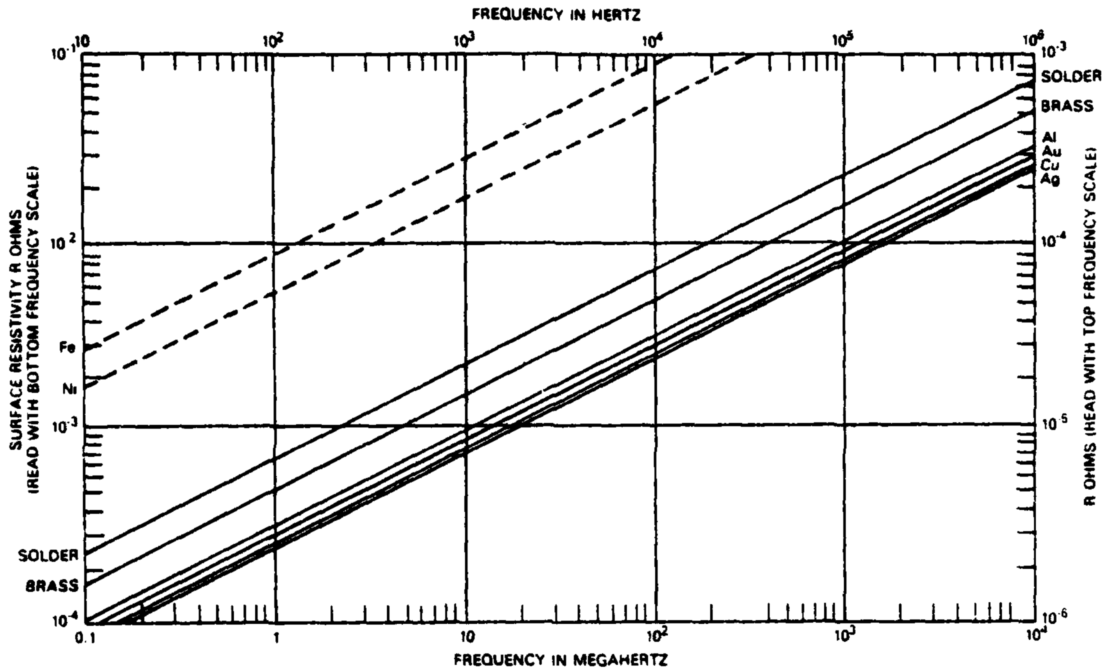


Fig. 6 — Conductor resistivity as a function of operating frequency

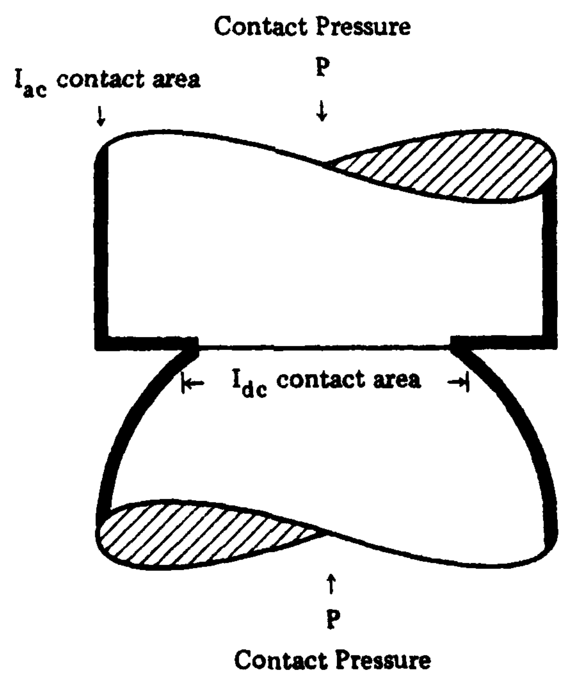


Fig. 7 — Ideal contact junction

Unfortunately, contacts are not as perfect as shown in Figure 7, but because of asperities, are more nearly as shown in Figure 8. This rough contact junction would appear considerably degraded at dc but may not be much different than Figure 7 for ac. Experimentally, it is often found that the IMG from a given connector will vary with contact pressure but not always be minimum at maximum pressure. One possible explanation is that with maximum pressure, the RF surface contact is warped or otherwise degraded at the expense of a better dc contact. Contaminants (oxides, sulfides, lubricants, etc.) tend to be pushed to the outside RF surface area, another possible contributor to poor performance. Gold plated contacts, in spite of the somewhat higher surface resistivity than silver for example, have been found to consistently give lower IMG levels than any other surface, apparently because of the relative freedom from corrosion products. Such contacts also show less criticalness to contact pressure, apparently because of the malleable characteristic of gold and the reduction of asperities. However, the use of a nickel undercoat to prevent base metal migration through gold plated surfaces must not be employed because of the ferromagnetic IMG interference caused.

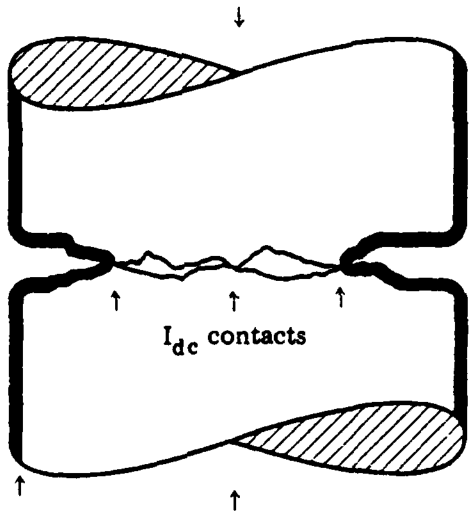


Fig. 8 — Imperfect contact junction

Figure 9 indicates the characteristic pin and socket arrangement usually employed for the center conductor contacts of coaxial connectors. The shaded surface area in the magnified view again illustrates the extremely small RF contact area relative to the dc contact area. Increased penetration depths of pins into sockets, although reducing dc contact resistance, have little effect on RF performance. As with the previous butt joints, IMG is often found to vary until "good seating" is secured. Again, the use of gold plating on both pin and socket appears essential for minimizing IMG.

Contact imperfections are also possible with the outer conductor elements of coaxial connectors. Construction practices today are, in some respects, inferior to what they were 30 years ago. For example, a potential source of IMG and contact failure has been the relatively insecure contact made between the outer conductor sleeve, and the main body of N male type connectors, accomplished by crimping. Mating, demating, shock, vibration, temperature, etc. eventually loosen this form of attachment, causing intermittent metal-to-metal contact, a large IMG source, or in other cases, complete failure, or breaking off of the contact ring. It should be noted that during and for a while after World War II, this type of connector problem did not exist because the outer conductor contact of the device

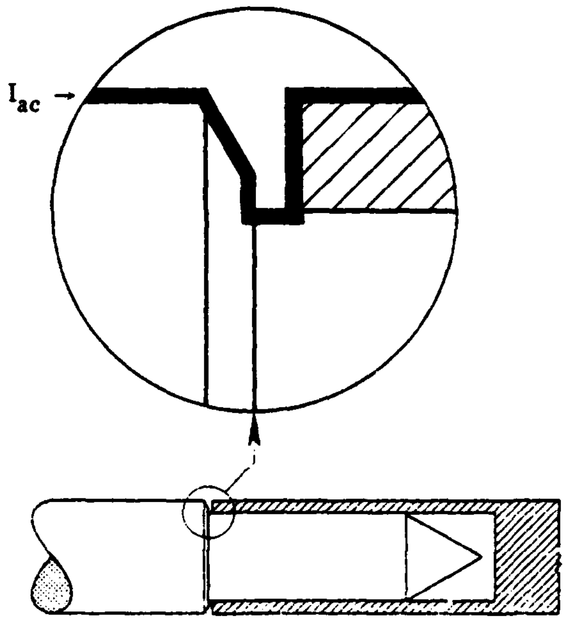


Fig. 9 — Typical pin-socket center conductor RF path

was machined from one piece of brass, which included the connector body. However, most manufacturers now crimp this body contact for reasons of economy. Although the original one piece construction is preferred, a full surface crimp, as used on certain connector types and by some manufacturers, is considered a minimum design. There are many similar instances too numerous to relate here. The need to use semi-rigid coaxial cables to obtain greater shielding has brought about many non-standard connector designs which have not yet been perfected. MIL-C-39012 only applies to flexible braided cable type connectors, except for the type SMA connector. A thorough re-evaluation of all cable-connector interfaces for both the center and outer contacts is urgently needed, based upon the NRL connector study.

CONCLUSIONS

It has been shown in this paper that the threshold sensitivity of many radio communication systems is currently limited, not by the associated low noise amplifiers (which were specially designed at high cost), but by IMG RFI which occur in improperly constructed RF connector hardware. The major contribution to this system performance degradation arises from the use of ferromagnetic materials (such as stainless steel or nickel plating) for electrical conducting elements in RF connector hardware, a practice which has been adopted by industry without sufficient research or user-consultation. This metallurgical problem can be corrected by returning to the use of non-ferromagnetic materials as previously employed. The long standing RFI problem associated with kovar or similar ferromagnetic hermetic seal type connectors can be also be elminated by use of recently developed non-ferromagnetic seals.

The contact nonlinearity problems have generally arisen from "short-cut" fabrication practices which have been adopted by manufacturers in recent years to reduce cost. These practices which differ with each connector type, should be permitted only if they do not detract from device performance and/or reliability.

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